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Research Department Report

RADIO-CAMERAS:

The development of radio systems for portable cameras used in television production

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RADIO-CAMERAS: THE DEVELOPMENT OF RADIO SYSTEMS FOR PORTABLE CAMERAS USED IN TELEVISION PRODUCTION

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Summary

Mobile and portable television cameras are often used for television outside broadcasts, and for live programmes, a camera is connected to the vision mixer using either a cable or a radio link. The radio option, now known as a 'radio-camera', has become very popular because it affords the producer greater flexibility in the choice of camera shots.

In its simplest form, a single-operator radio-camera system uses a small microwave transmitter with an omnidirectional transmitting antenna, attached to the camera. This provides the required insensitivity to the orientation of the camera but multipath propagation of the radio signal can seriously degrade the received television pictures.

Investigation of means to combat multipath propagation has been the subject of an intensive programme of work at Research Department, and this has resulted in the development of special transmitting antennas which use circular polarisation, as well as a novel tracking system using directive antennas. Some of these developments are now used regularly by Television Outside Broadcasts.

The Report describes this work, starting with an outline of the various configurations for a radio-camera system and covering the history of the use of such systems in the BBC. Theoretical and practical aspects are then discussed, and descriptions are given of the current 2.5 GHz and 12 GHz systems, and the new switched-antenna system which is presently being developed.

Index terms: *Radio-cameras; TV broadcasting; TV links; antenna; SHF propagation; multipath propagation; FM; tracking systems*

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1. INTRODUCTION

Mobile and portable television cameras are often used in the BBC for outside broadcast (OB) coverage of sports events, concerts and news items. They offer producers and camera operators a great deal of flexibility in their choice of camera shots, especially when used close to the 'action'. Nowadays, for recorded programmes a variety of portable VTRs and 'camcorders' are available, but for live programmes a camera must be connected to the vision mixer using either a cable or a radio link.

A long, trailing cable is an encumbrance to the camera operator, and can present a trip-hazard to others, so the alternative of using a radio link is very popular; it allows the operator much greater freedom of movement. Also, in the live coverage of moving action, a camera is often mounted on a vehicle, and in this case a radio link is essential. The general arrangement of a portable camera coupled to a radio-link transmitter, often powered by the same battery, has become known as a 'radio-camera'.

A radio-camera can be configured in several ways, there are single and dual-operator systems for a hand-held camera and several arrangements for a camera mounted on a vehicle. The configuration which is currently receiving the greatest attention is the single-operator hand-held radio-camera, and this is causing a minor revolution in OB operations because of the greatly increased flexibility and mobility it affords. A typical application is shown in Fig. 1, taken at the conclusion of the Ladies Final of Wimbledon 1988. The success of this approach owes a great deal to the development of specialised transmitting antennas.

2. TYPES OF RADIO-CAMERA SYSTEM

An important requirement is that the radio link carrying the camera signal should be insensitive to the location or orientation of the camera. From an RF viewpoint, radio-camera systems fall into two categories: those which use a directive transmitting antenna and those which use an omnidirectional antenna. A directive receiving antenna is commonly used in both cases.

The first type is an extension of the point-to-point radio link principle, used widely in OB operations. Provided that a clear line-of-sight path is available between the transmitting and receiving antennas, this type offers reliable communication of the television signal. However, since the transmitting antenna is directive it must be kept pointing towards the receiver, and this can require either an additional

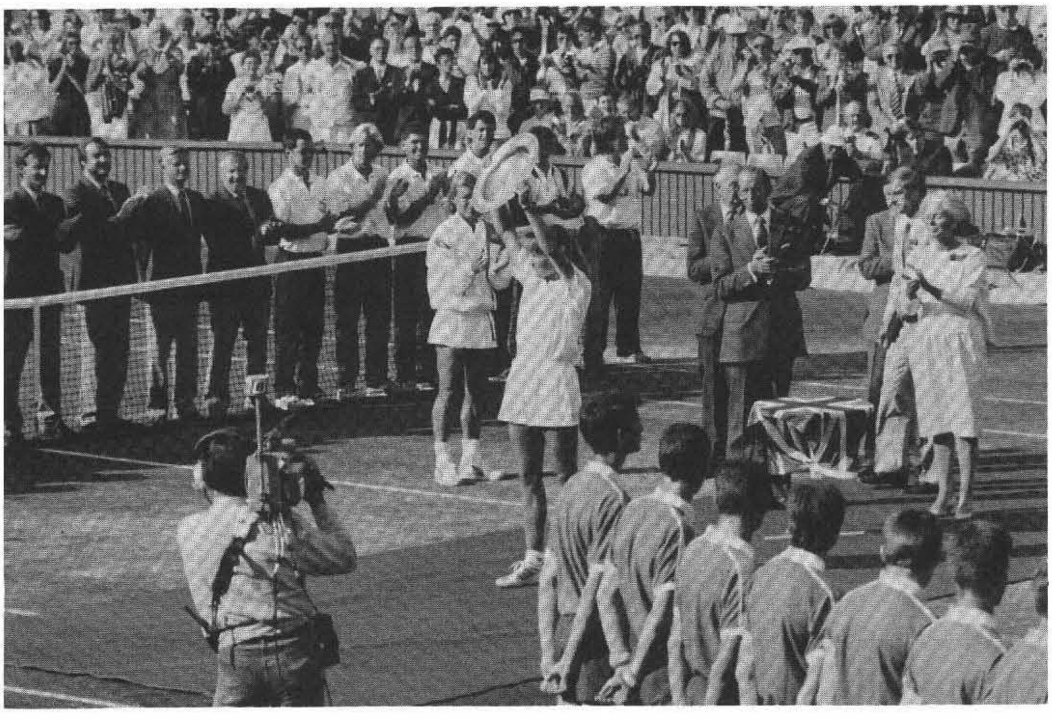

Fig. 1
A typical application for a radio-camera.

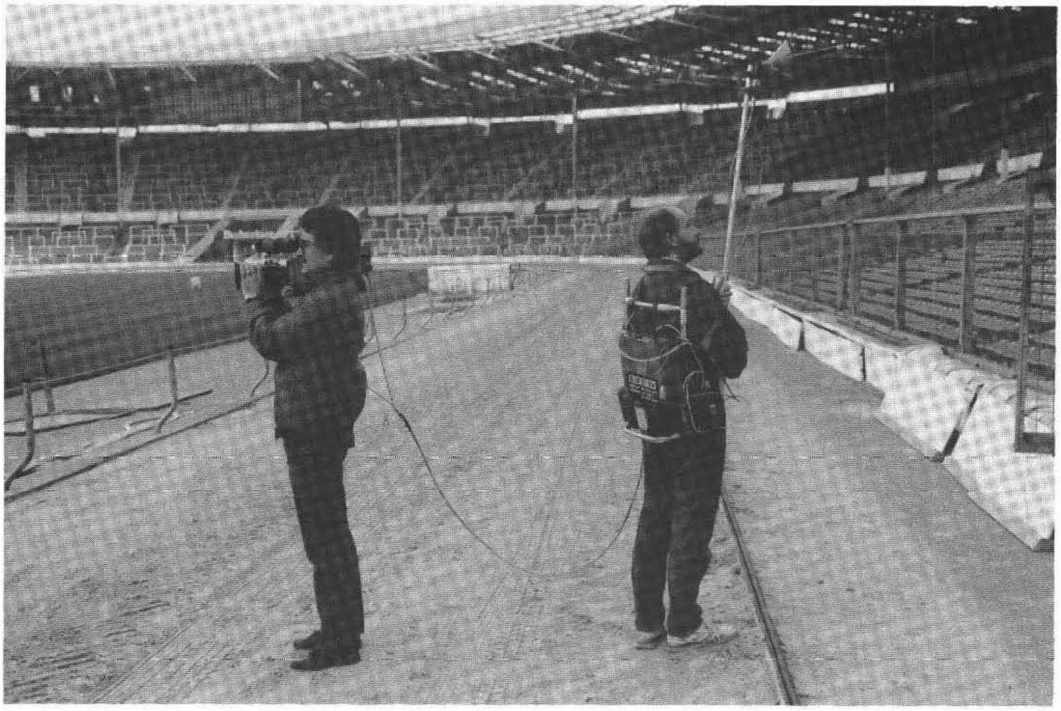

Fig. 2
A dual-operator radio-camera.

operator or the use of an automatic tracking system; both approaches have some attendant complications. For a hand-held camera, the dual-operator approach requires the second operator, tethered to the camera by a cable, to follow the camera operator whilst keeping the transmitting antenna 'on track', and this can involve walking backwards! An example of this approach is shown in Fig. 2. Tracking systems will be discussed later, but in some cases, such as a 'roving eye' vehicle travelling on a linear path, it is possible to use a fixed directive antenna.

The second type is simpler since the camera operator alone can be equipped with the radio-link transmitter and transmitting antenna. With this arrangement, access can be gained to areas that could not be covered using a cabled camera, and in some cases not even with the dual-operator system (the 'umbilical' cable is still viewed as a potential hazard at some sports venues). Alternatively, the camera and radio equipment can be mounted in a vehicle, such as a racing car, to operate unattended, as illustrated in Fig. 3.

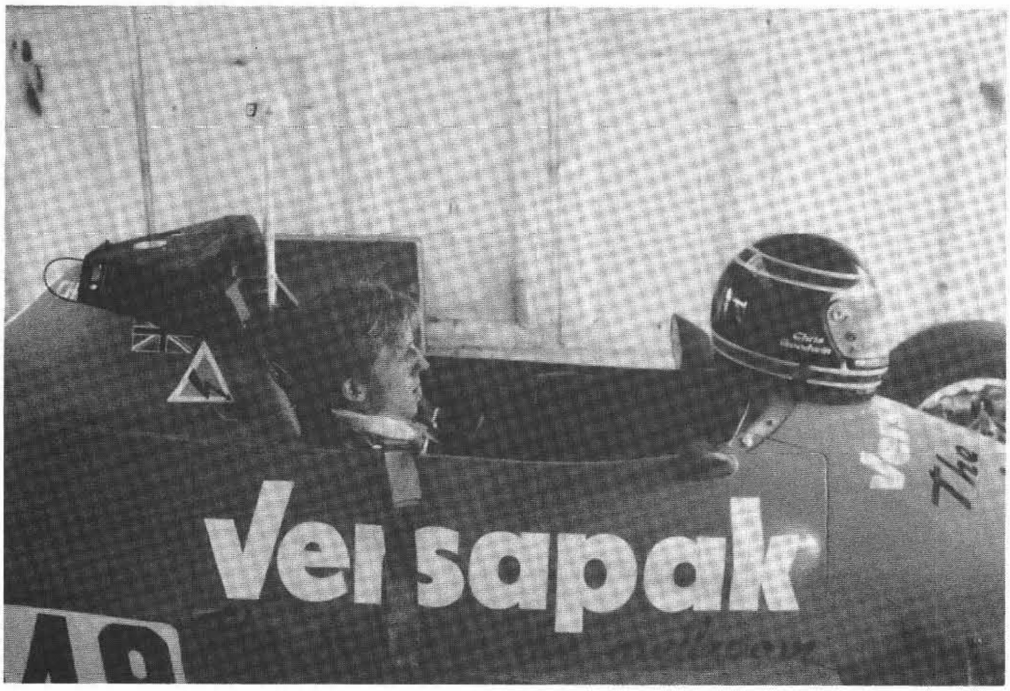

Fig. 3
A radio-camera mounted on a racing car.

Since the transmitting antenna is omnidirectional in this case, at least in the azimuth plane, there is no sensitivity to its orientation and, ideally, the radio-camera would be able to cover all areas where a line-of-sight path is available. The practical case is often less than ideal because the transmitting antenna 'illuminates' objects and surfaces all around, and these can give rise to spurious reflected signals, which can also be received by the distant receiver. Interference between the direct and reflected signals can affect the operation of the radio link by causing distortion of the received television signal. This effect is known as multipath propagation and the result is multipath distortion, which can be largely eliminated by using a directive transmitting antenna.

Some other configurations are used, but they are generally hybrids of these two types of system. For example, a camera is carried on a motorcycle during the live coverage of the London Marathon. The only practical way to sustain continuous communication whilst travelling is to relay the signal using a helicopter overhead. The link from the motorcycle to the aircraft uses directive antennas with fairly wide beamwidths to accommodate rolling when corners are negotiated, but since it is directed upwards it suffers little multipath distortion. The second link, from the aircraft to a rooftop receiver, uses an omnidirectional transmitting antenna slung beneath the helicopter; this link operates in nearly 'free-space' conditions.

3. HISTORY

The course of radio-camera development has taken us from very simple systems, which would only work well in an uncluttered environment, through several changes of antenna types and frequency band, from Band I (40 MHz) to 12 GHz and above. Modern systems pay a great deal of attention to multipath propagation and can allow the coverage of as much as 80% of the ground-level area in a highly cluttered sports stadium.

Some of the credit for this progress is due to the equipment manufacturers, especially for the provision of miniature SHF transmitters, but the major steps towards improving the resistance to multipath distortion have been taken by the broadcasters. In the BBC, this progress is the result of collaboration between Research Department, developing improved antennas and associated electronics, and Television Outside Broadcasts, the end user.

The early VHF and UHF systems used linearly polarised antennas (horizontal as well as vertical) and were mainly used with vehicle-mounted cameras. These used directive antennas and were quite successful. There was even a scheme for a roving-eye which used a gyro-compass to keep the antenna pointing to a constant bearing as the vehicle moved around. This is not always appropriate, especially when the radio-camera is moving laterally with respect to the receiver and is not a long distance away.

There were a few 'back-pack'* configurations for single-operator use, and these used omnidirectional, linearly polarised transmitting antennas. They were quite vulnerable to multipath propagation, and rarely provided consistent, high quality television pictures whilst on the move, but these did demonstrate the potential of the single-operator approach.

With the evolution of miniature SHF radio-link transmitters, it became possible to integrate the electronics and the transmitting antenna into a package small enough to be mounted on the back of a portable camera. Then the only remaining problem was multipath propagation.

In 1985, work was in progress at Research Department investigating a miniaturised tracking system for a 12 GHz radio-camera using a directive transmitting antenna mounted on a motorised platform. The portable equipment was configured as a back-pack, which is shown in Fig. 4, and the horn antenna on its mount is shown in Fig. 5. The direction in which the horn pointed was determined by a data signal sent to the back-pack from the distant SHF receiver, using a VHF radio link, and at the receiver a microcomputer was used to implement a 'step track' algorithm. Data representing the strength of the received signal was input to the microcomputer, which sent commands to the back-pack to turn the horn in one direction or the other in order to optimise the signal strength. Thus the aim of the system was to emulate the dual-operator approach.

Although this system worked, its performance was impeded by the limited rate of rotation of the stepper-motor used, and this led to the conclusion that a 'solid-state' approach was preferred to any tracking system involving mechanisms.

In 1987 the Italian broadcaster, RAI, demonstrated a single-operator radio-camera system at the World Athletics Championships in Rome. This used an omnidirectional transmitting antenna working at 1.9 GHz, but with circular polarisation (CP), and this helped to overcome the multipath problem. The type of antenna used by RAI was an array of four slanted dipoles, sometimes known as a Lindenblad

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* The arrangement whereby much of the electronic equipment is carried on the back of the operator; not to be confused with the modern alternative of a 'camera pack', where miniaturised equipment is attached to the back-end of the camera.

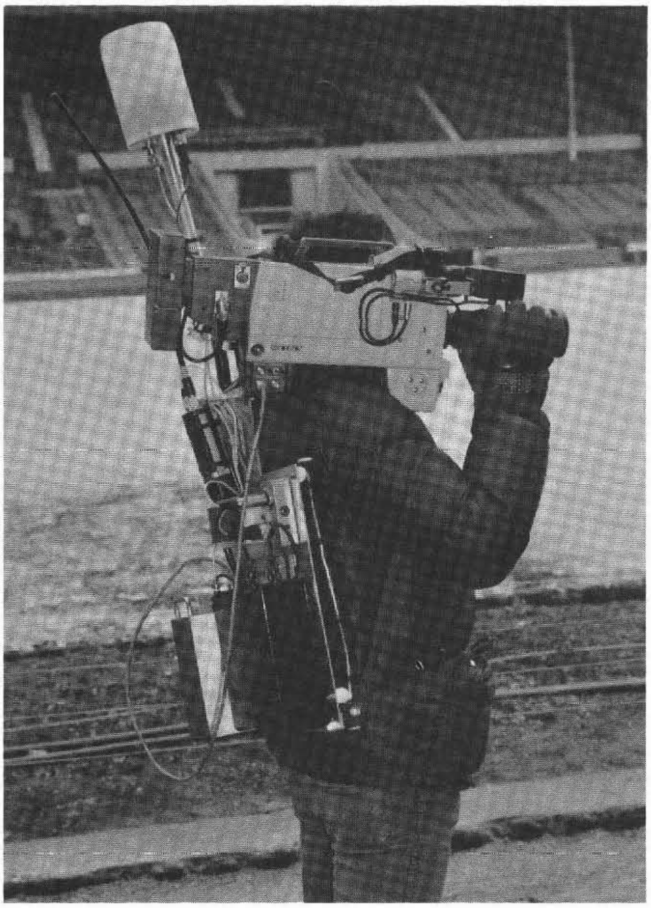

Fig. 4 - The experimental 12 GHz back-pack.

array after its original inventor[1]. RAI had built antennas based on this principle following work reported in the RCA Review[2]. Following this lead, experiments were carried out in the BBC using similar antennas at 2.5 GHz and, by designing such antennas from first principles, ways were found to improve the purity of polarisation. This led to the introduction into service of a series of 2.5 GHz single-operator radio-cameras using transmitting antennas developed by Research Department, and these were most successful.

Around this time, some of the equipment manufacturers were beginning to realise the potential demand for radio-cameras and started to offer omnidirectional CP antennas for the 2.5 GHz band. In comparative tests with the antennas developed at Research Department, the proprietary antennas were found to have inferior radiation characteristics. In view of the situation later encountered with the 12 GHz antennas, described in the following paragraph, this was a significant finding.

During the preparations for the 1988 Olympic Games in Seoul, it became apparent that no frequency allocations in the 2.5 GHz band would be available for the BBC to use, so attention turned to other frequencies. Conventional radio-link receivers were available for the 12 GHz band, and equipment manufacturers were found with the capacity to manufacture miniature transmitters (actually 2.5 GHz transmitters fitted with external frequency multipliers) and a CP feed for a receiving dish antenna, within the available time. As appropriate bandwidth was available, the 12 GHz band was used at Seoul.

One of the manufacturers had indicated that a suitable omnidirectional CP transmitting antenna could be provided, but when this was delivered it was found to have very poor polarisation characteristics. No other suitable antennas were readily available, so the requirement was presented with great urgency to Research Department. Within the space of five weeks a new type of omnidirectional CP antenna was developed for the 12 GHz band. The inspiration for this came from a satellite beacon antenna used at similar frequencies, and again this proved to be very successful.

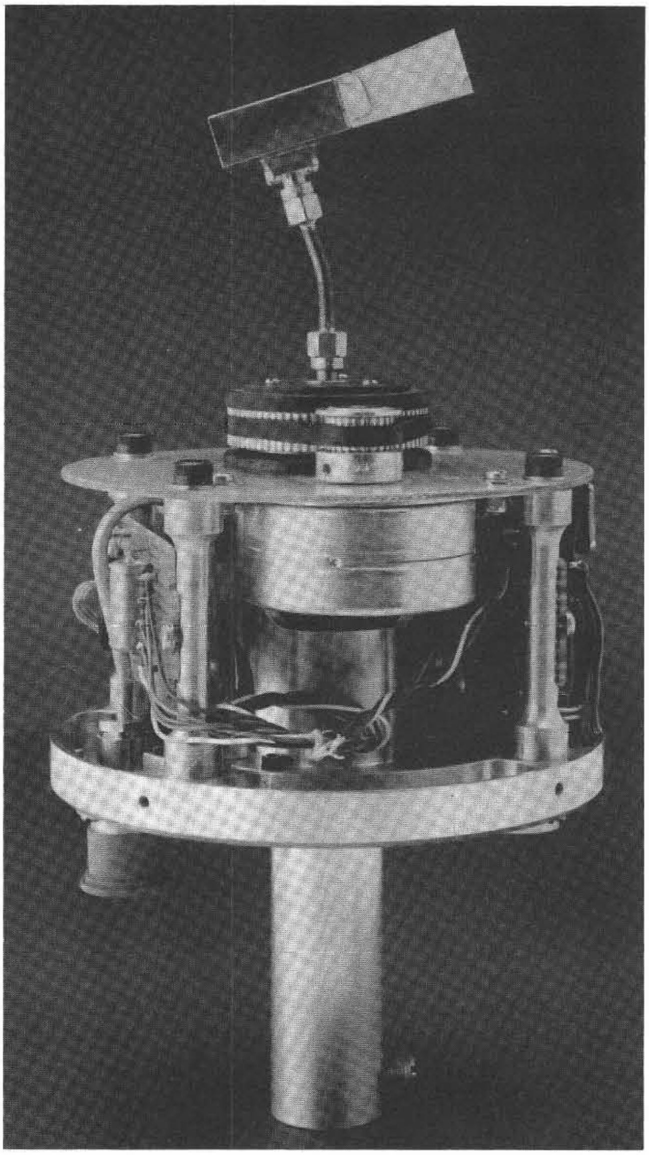

Fig. 5 - The horn antenna on its rotatable mount.

It is true to say that nowadays, proprietary omnidirectional CP antennas are available for the 2.5 GHz and 12 GHz bands with the required radiation characteristics; sufficiently uniform radiation patterns in the horizontal plane and adequate purity of polarisation. Therefore, the need for the BBC to continue research in this field has diminished, but for ergonomic reasons, the antennas developed at Research Department are still preferred to some of the commercial designs.

In the mean time, BBC research work has continued on the 12 GHz solid-state tracking system, and this has led to the development of a novel switched-antenna system which will be described later.

Apart from RF devices, one development which has greatly simplified radio-camera operations is the digital field-store synchroniser. Nowadays, the television signal received from a radio-camera is always passed through a synchroniser to correct its timing before it is presented to the vision mixer, so the camera can run on its own in-built sync. pulse generator. In the early days, prior to the availability of synchronisers, the options were: to make non-synchronous cuts, to synchronise all other picture sources to a single radio-camera, or to use a 'genlock' system requiring a return radio link to the radio-camera; all of these approaches have severe drawbacks.

Presently, attention is turning to the few remaining disadvantages of a radio-camera relative to a cabled camera, and another recent development is the application of remote control to camera adjustments such as the iris opening and black level. A working system has been developed by Television Outside Broadcasts to control up to sixteen radio-cameras independently over an existing radio talkback channel.

4. THEORETICAL ASPECTS

There are two fundamental requirements for a working radio-camera system. Firstly, a propagation path must exist between the transmitting and receiving antennas. Then, for the longest path envisaged, there must be sufficient transmitter power, receiver sensitivity and antenna gains to achieve an adequate signal-to-noise (S/N) ratio. Modern equipment allows a considerable margin in this respect, yielding free-space maximum path lengths of a kilometre or more, even when a low-gain omnidirectional transmitting antenna is used. Link budgets for some typical radio-camera systems are presented in Appendix 1.

The two main drawbacks to using a radio-link, rather than a cable, are path blocking and multipath propagation.

4.1 Path blocking

Path blocking, often caused by obstacles such as pillars, fencing posts and people, attenuates the RF signal, and this reduces the carrier-to-noise (C/N) ratio of the received signal. Television OB radio links in the BBC commonly use FM, and as the C/N ratio is reduced the S/N ratio of the demodulated television signal diminishes. If the C/N ratio falls below a threshold of about 11 dB, 'threshold noise' spikes start to appear in the television signal, and these can upset the operation of devices which use sync. separators, like monitors and VTRs. This threshold is caused by the failure of the FM demodulator in the receiver and is one of the few fundamental drawbacks to using FM. Therefore, a certain degree of path blocking can be tolerated before the threshold noise appears, and the result is simply a reduced S/N ratio, but beyond that degree the demodulated video signal can become unusable.

In principle, the resistance to blocking can be improved by using greater transmitter power or a lower radio frequency. The first option is usually inhibited by considerations of safety when the transmitting antenna is operated close to personnel, and for a hand-held radio-camera the maximum power is usually limited to 250 mW, although 2 W transmitters are available. The power must also be limited when batteries are used for the primary supply. The second option, resulting from diffraction at the edges of the obstacle, can be countered by the reduction in the gain of the directive receiving antenna at lower frequencies, if it is to remain of a practical size. This antenna is usually pointed manually towards the radio-camera, and often there is insufficient room for anything larger than a 1.1 m reflector antenna. However, the receiving antenna can sometimes be located high up, slanting the propagation path up and away from many potential obstacles. A typical example is shown in Fig. 6; a 1.1 m reflector antenna located in a commentary box at Wembley Stadium.

4.2 Multipath propagation

Multipath propagation presents the major problem to systems which use omnidirectional transmitting antennas. In 'free-space' conditions, the simplest of systems would work, even using an omnidirectional receiving antenna, but most OBs occur at locations where there are a large number of potential reflecting objects, such as fences, stadium buildings and overhanging roofs. The following explanation is limited to only one reflected path, although in practice there will usually be many.

When multipath propagation occurs, the reflected signal arrives at the receiver later than the

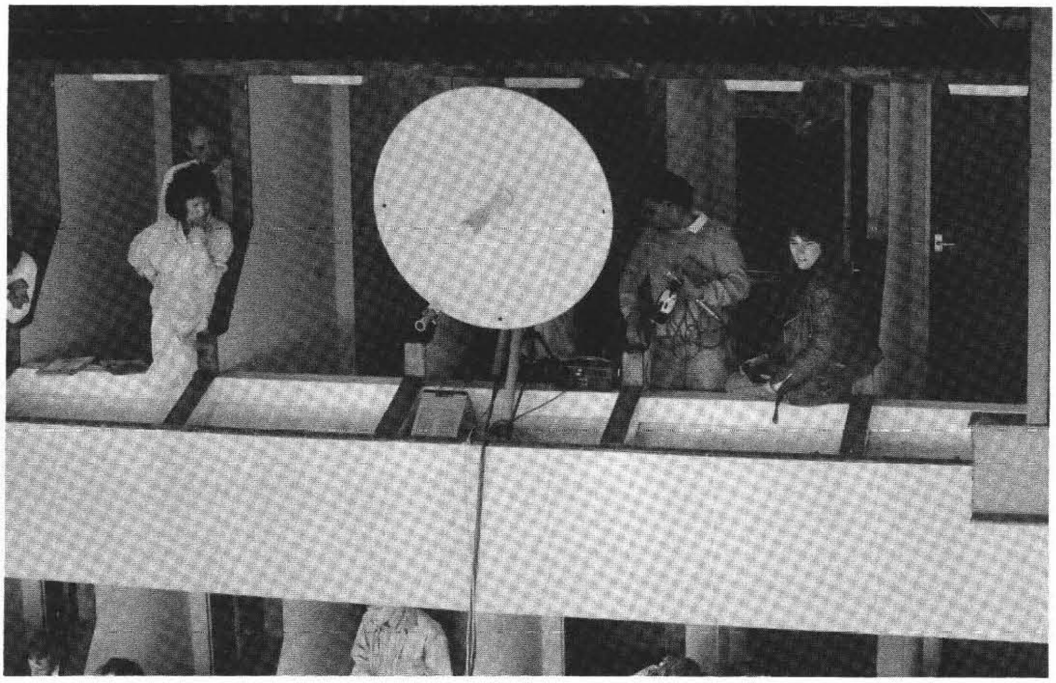

Fig. 6 - A typical location for the receiving antenna.

direct signal, and as the two signals combine in the receiving antenna, interference between them imposes a 'comb filter' frequency response on the RF channel. The transmission minima or 'nulls' in this response are generally more damaging to the performance of the radio link than the maxima since they can have depths in excess of 6 dB. The actual depths depend on the difference between the amplitudes of the two signals, and this depends on the difference between the two path lengths (because of spherical spreading) and on the radio-frequency 'scattering' properties of the reflecting object. The spectral density of the minima and the frequencies at which they occur are interrelated, and they depend on the path length difference. The density increases at higher frequencies and when the reflecting object is further away from the direct path.

When this comb filter response is applied to an FM television signal it can have several adverse effects, known collectively as multipath distortion.

Firstly, if the attenuation suffered by the reflected signal is small, such as when the reflection is caused by a sheet of metal nearby (e.g. the side of a vehicle), the depth of the minima will be great. Then, whenever the FM signal passes through the frequency of a minimum, the C/N ratio can fall below the FM threshold, with the result that the receiver can output a burst of noise. In its least damaging form, this effect produces noisy areas in the received pictures, but the worst example occurs when a minimum falls on the frequency which corresponds to the bottoms of the sync. pulses. Then the normal synchronisation process is rendered inoperative and only devices which incorporate sync. separators with a 'heavy flywheel' action can make use of the signal. Unfortunately, digital synchronisers seldom fall into this category and in the absence of incoming sync. pulses most synchronisers either freeze-frame or cut to black until valid sync. pulses reappear. Freeze-framing can give the unacquainted the impression that the picture material is not live, so this must be avoided.

Secondly, the spectrum of an FM signal carrying high frequency modulation components has the characteristic form of a carrier and sidetones which have symmetrical amplitudes. When a transmission minimum appears at the frequency occupied by a first-order sidetone this can have the effect of reducing the modulation index of the FM signal; then, for instance, the amplitude of the colour subcarrier in the received signal may be attenuated. As the mean luminance level changes, the FM signal sweeps across the RF channel, in and out of the minimum, so the result is differential gain variation. This can be ameliorated to some extent by passing the signal through a chrominance AGC circuit, and this is often done in BBC operations.

Thirdly, considering the FM signal in the same way, when a minimum appears at the centre frequency of the FM spectrum (the frequency occupied by the zero-order tone, or the 'carrier'), this can have the opposite effect of increasing the FM index; then the amplitude of the colour subcarrier may be magnified. The worst result of this effect occurs when the magnitude of the received colour subcarrier becomes so large that clipping occurs in the video stages of the receiver, or the equipment which follows it. This can give rise to spurious 'luminance' components.

These are the most noticeable effects, but they tend to be intermittent and, significantly, of short duration. If the path-length difference changes by only a small fraction of the wavelength, the type and degree of distortion can change significantly. Thus, with the very short wavelengths used, the effects of multipath distortion can be ameliorated, even by minor movements of the camera, or of the reflecting object. Also, since AC coupling is generally used in an FM transmitter, the absolute frequencies of features of the transmitted signal change with variations in the average picture level (APL).

It can be shown that the locations of places where transmission minima occur, at a particular radio frequency, are distributed with a spatial density which is also a function of the frequency and the path-length difference. For a given multipath environment, in the higher frequency bands such as 12 GHz, the spatial density of minima will be greater than for a lower frequency band, such as 2.5 GHz, so minima should be encountered more frequently as the radio-camera moves around. This might be expected to cause greater degradation to the received pictures but, in practice, 12 GHz radio-camera systems have not been found to be inferior to their 2.5 GHz counterparts. One explanation is that the scattering properties of typical reflecting objects offer more attenuation to the shorter wavelength signals.

Alternatively, multipath distortion can be considered to be the result of co-channel interference, where the interfering signal has the same modulation characteristics as the wanted signal, but subject to a time delay. In many cases, increasing the transmitter power does not help because this simply increases the magnitudes of both the wanted and interfering signals.

The effects of multipath propagation are considered in more detail in Appendix 2.

Clearly, the situation is improved when the number of possible routes for multipath propagation is reduced by using a pair of directive antennas, and the dual-operator and 'roving eye' systems rely on this. Using a directive antenna only at the receiving end of the link helps, but this could never suppress a reflection from an object directly behind the radio-camera.

4.3 Circular polarisation

Another way to provide a degree of immunity to multipath propagation, is to use circular polarisation (CP) for the radio signal, as mentioned earlier. There are two senses of CP, and antennas can be made to discriminate between them in the same way that linearly polarised antennas can discriminate between vertically and horizontally polarised signals.

The useful property of CP is that specular reflection of the radio wave causes the sense of polarisation to be reversed. Practical reflecting objects do not cause pure, specular reflections so, in general, the reflected wave will contain components of both senses. The important feature is that the component with the sense that was transmitted is attenuated selectively on reflection, and this does not occur using linear polarisation.

Hence, if the radio-camera and the distant receiver are both equipped with antennas which discriminate in favour of the same sense of CP, the signal propagating over the direct path will be received without additional attenuation but reflected signals will be attenuated. The surfaces of most reflecting objects found at OBs are rough in terms of the RF wavelength, and the consequent scattering leads to further attenuation after two (or more) reflections, so the signal strength is then usually insignificant.

This principle provides sufficient benefit to allow the use of a CP transmitting antenna with an omnidirectional radiation pattern in the azimuth plane, and this is the key to simple, hand-held radio-camera operation. With the application of chrominance AGC, this can allow coverage of as much as 80% of the ground area of a highly-cluttered sports stadium.

In the single-operator radio-camera, the transmitting antenna is usually attached to the body of the camera so it must have a fairly wide beamwidth in the elevation plane to allow the operator freedom to take shots at inclined angles, and this means the ground will be illuminated. The effects of reflections from objects around the radio-camera are generally intermittent, coming and going as the operator moves about, but the geometry of the ground reflection can remain constant during these movements.

Since CP provides only a limited benefit, it is important that the small but continuous multipath contribution from the ground reflection should be minimised, so the receiving antenna is usually located as high up as possible. This increases the angular separation between the direct path and the ground-reflected path as it applies to the transmitting antenna, so some benefit can be gained from its radiation pattern in the vertical plane. However, this makes little difference to the angular separation at the receiving antenna, and this is often as little as 2°.

5. PRACTICAL ASPECTS

At the present time, the frequency bands used most often for BBC radio-cameras are 2.5 GHz and 12 GHz, although other allocations for OB microwave links at 3.5 GHz, 5.5 GHz, 7 GHz and 48 GHz are being considered. The 2.5 GHz band presently represents the best compromise between equipment performance and antenna compactness, but the number of channels available is severely restricted. More equipment is becoming available for the 12 GHz band, and this is allowing more widespread use of radio-cameras, even multiple radio-cameras at the same OB. At the end of 1990 more than ten radio-camera systems were in regular use in the BBC.

Whilst the radio-camera principle removes the need for a trailing cable, in a single-operator system it does burden the camera operator with the transmitter, the transmitting antenna and, perhaps, an extra battery. In view of this, efforts have been made to preserve the balance of the camera, and to procure the most compact and lightweight equipment. Antennas have been mounted on masts of the minimum possible length, just long enough to clear the operator's head. For the 2.5 GHz and 12 GHz systems using omnidirectional CP transmitting antennas, a common mounting arrangement has been devised with adaptors to suit all of the hand-held cameras presently used by Television Outside Broadcasts.

5.1 Options for the transmitting antenna

For dual-operator systems, an antenna beamwidth of about 30° is suitable. This is a compromise between suppression of multipath propagation and ease of keeping the antenna 'on track'. Early systems used short log-periodic dipole arrays for the UHF band[3]. Later, a 2.5 GHz disc Yagi array[4] was designed for this application, offering CP as well as linear polarisation. CP has become the standard for most radio-camera operations, and latterly a short axial-mode helix has been used.

Vehicular systems have also used these antennas, as well as a number of dipole-reflector configurations at UHF. Some other types of CP antenna are used, such as crossed-dipoles in front of a reflector, and a variation on this theme, known as a 'wilted dipole'[3], is often used at both ends of a ground-to-helicopter link. This antenna was designed for use on a helicopter, and it exhibits good back-lobe suppression to eliminate multipath effects caused by the rotor blades. It has a large beamwidth, about 180°, with fairly good axial-ratio*; 3 dB to 8 dB over the beamwidth. Recently versions of this antenna for the 2.5 GHz, 3.5 GHz and 5.5 GHz bands have been manufactured to the BBC design.

For single-operator systems, all the early VHF and UHF transmitting antennas were variations on the dipole[3], and early 2.5 GHz systems used a vertical discone. The first successful 2.5 GHz omnidirectional CP antenna was a 'Lindenblad array'. This has a number of slanted dipoles mounted around a central vertical support mast, and the dipoles are driven in-phase using a power splitter. Its radiation patterns are similar to those of a single vertical dipole, but CP, and this is still the preferred antenna for this application at 2.5 GHz.

For the 12 GHz band, dipoles are rather difficult to manufacture, so another option is to use slots cut in the wall of a waveguide. Such an antenna was designed for the 1988 Olympic Games in Seoul. This has six pairs of crossed slots cut in the wall of a circular waveguide. The power splitting, to feed the slots equally, is accomplished by feeding the waveguide with a circularly polarised mode, and this is generated using a septum polariser. This antenna would normally be omnidirectional in all planes, but a pair of external choke-sleeves has been added to reduce end-fire radiation.

5.2 Options for the receiving antenna

Dish reflector antennas are popular for the receiving end of the link, since these are in general OB use, and log-periodic dipole-array feeds and log-spiral feeds[3] were designed for some of the early UHF systems. Some other types of antenna have also been used, such as long Yagi arrays for linearly polarised VHF and UHF links.

For the present 2.5 GHz systems, CP feeds have been procured to suit 0.6 m and 1.1 m reflectors; for the 12 GHz systems, feeds have been procured for 0.6 m reflectors. At 2.5 GHz the 1.1 m reflector antenna has about 5° beamwidth and the 0.6 m antenna about 11°; at 12 GHz the 0.6 m antenna has a beamwidth of about 3°. The 1.1 m diameter reflector is not used at 12 GHz because its beamwidth would be too small for ease of manual 'tracking'.

Another type of CP antenna used is a broadside array of four axial-mode helices. This has the advantage that it gives the operator a clear view of where the beam is pointing. The disadvantage is that it provides less gain and has greater beamwidth than a reflector of the same size.

In a cluttered environment the best rejection of multipath propagation is achieved by using the smallest receiving antenna beamwidth, and hence the largest antenna. A large, high gain antenna is also needed when the path length is long, but sometimes a compromise has to be accepted because of lack of space. A great deal of practical experience has been built up in BBC Television Outside Broadcasts about which arrangement is most suited to a particular environment.

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* Axial-ratio is a measure of the purity of circular polarisation; 0 dB axial ratio corresponds to pure CP of one sense, and infinity dB corresponds to utterly impure CP, which is actually linear polarisation.

In most radio-camera operations the receiving antenna is pointed manually, and this is a relatively straightforward task although it can become tedious. The radio-camera can usually be seen clearly from the location of the receiver, and its apparent rate of angular motion is usually very small. However, an automatic tracking system could be used, along the lines of the Helitrak tracking receiver system, developed at Research Department for receiving radio-link signals transmitted from a helicopter[5]. This system uses a conventional 1.1 m reflector, fitted with a special feed which allows the antenna's beam to be offset by small angles, under electronic control. In this case the antenna is linearly polarised, but similar principles could be applied to a CP antenna.

In the following sections, descriptions will be given of the two radio-camera systems currently in use, and a new system being developed which uses switched directive antennas.

5.3 The 2.5 GHz omnidirectional CP system

A 2.5 GHz radio-camera using an omnidirectional CP transmitting antenna is shown in Fig. 7, where the miniature transmitter (manufactured by RF Technology Inc.) can be seen attached to the rear of the portable camera.

The antenna was designed at Research Department and is based on a Lindenblad array, which is an array of slanted dipoles; in this case four. This is shrouded by a glass-fibre radome, but in Fig. 8 the array can be seen with the radome removed. Each of the dipoles is fed by a Pawsey stub balun. The lengths of the dipole limbs, the angles of slant, and the lengths of the stubs have been optimised for best performance (viz. the radiation patterns, the polarisation and the impedance match). The four-way power splitter is contained in the central vertical support.

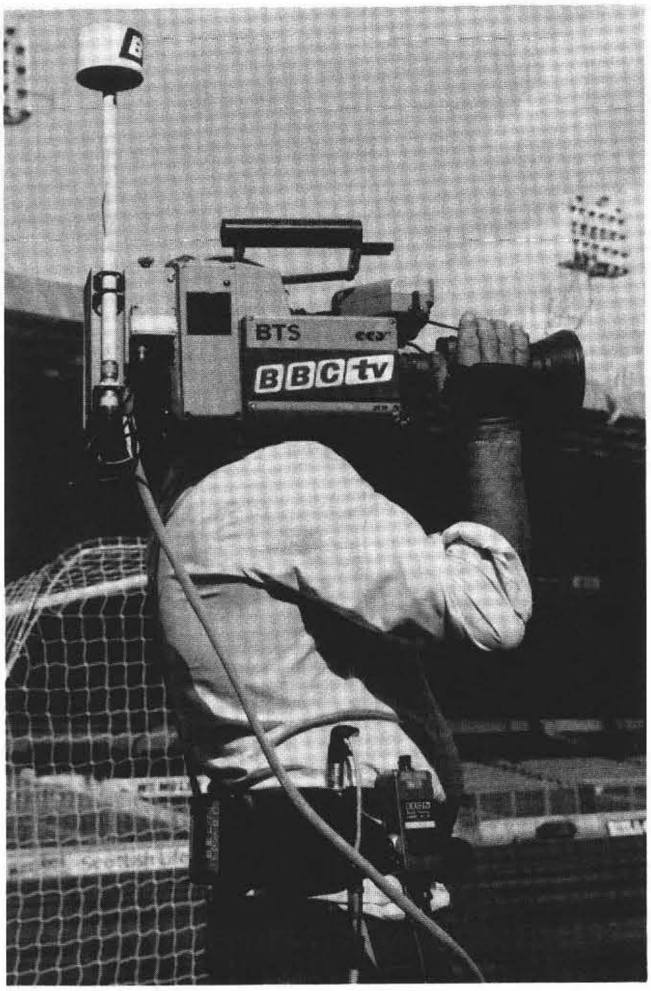


Fig. 7 - The 2.5 GHz single-operator radio-camera.

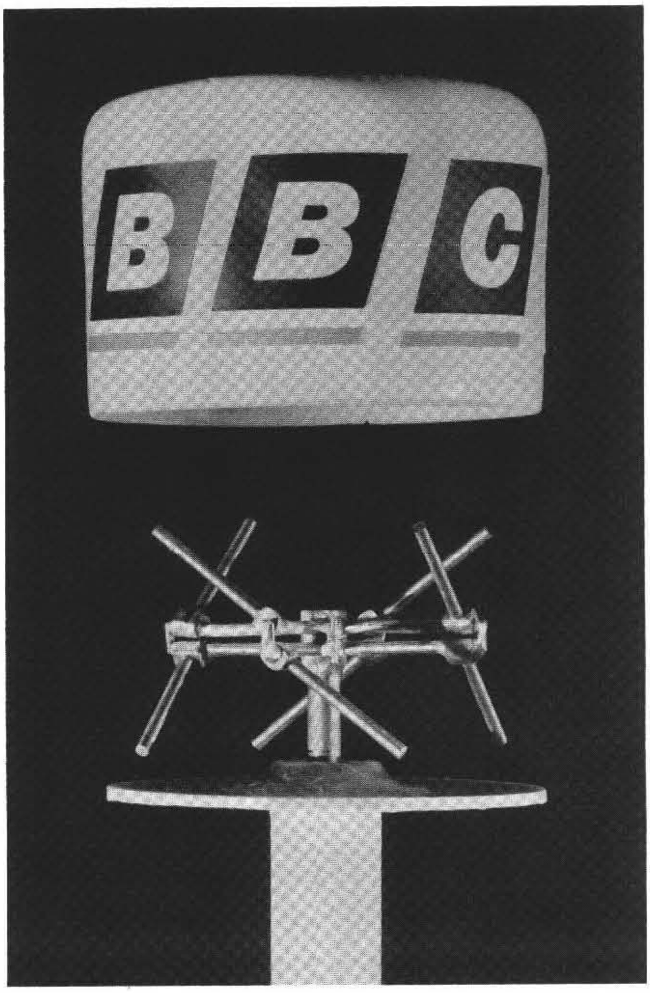
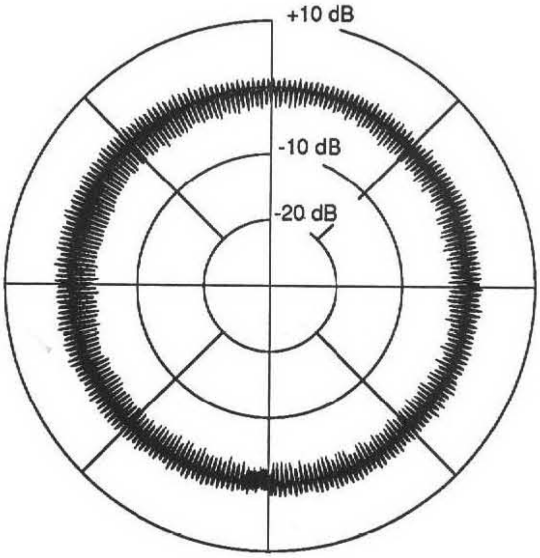


Fig. 8 - The 2.5 GHz transmitting antenna.

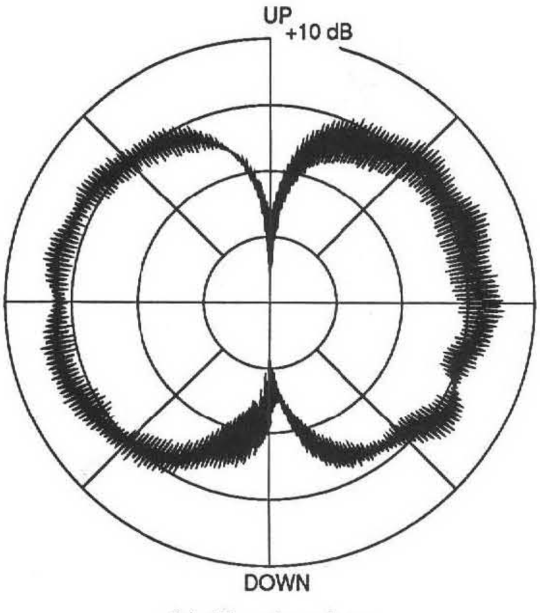
Later versions of this antenna were manufactured in small batches by an external firm, to BBC drawings, and the radomes were filled with polyurethane foam to make them more robust.

The radiation patterns for this antenna are shown in Fig. 9, measured in the azimuth and elevation planes. These patterns were measured using a linearly polarised source antenna rotating about the axis of its beam, so the magnitude of the undulations in each pattern displays the axial-ratio. The 'right-hand' sense of CP has been chosen, arbitrarily, for most radio-camera systems used in the BBC.

In the azimuth pattern, shown in Fig. 9(a), the width of the envelope of the undulations is between 3 dB and 6 dB; this corresponds to a cross-polar discrimination (XPD) varying between about 15 dB and 10 dB, respectively. The mean of the azimuth pattern is a circle, showing the required omni-directional response.



(a) Azimuth plane.



(b) Elevation plane.

Fig. 9 - Radiation patterns for the 2.5 GHz antenna.

The mean of the elevation pattern, shown in Fig. 9(b), is a lateral figure '8', very close to the response of a half-wavelength vertical dipole, and the deep null in the downwards direction helps to suppress the ground reflection. The wide beamwidth in the elevation plane allows the integrated hand-held radio-camera to be tilted. An axial-ratio of 6 dB or less is maintained at all angles of elevation, which is a fundamental requirement because spurious reflections can occur over a very wide angular range.

Similar radiation patterns are maintained over the frequency range 2.4 - 2.7 GHz.

5.4 The 12 GHz omnidirectional CP system

A 12 GHz radio-camera using an omni-directional CP transmitting antenna is shown in Fig. 10. This antenna was also designed at Research

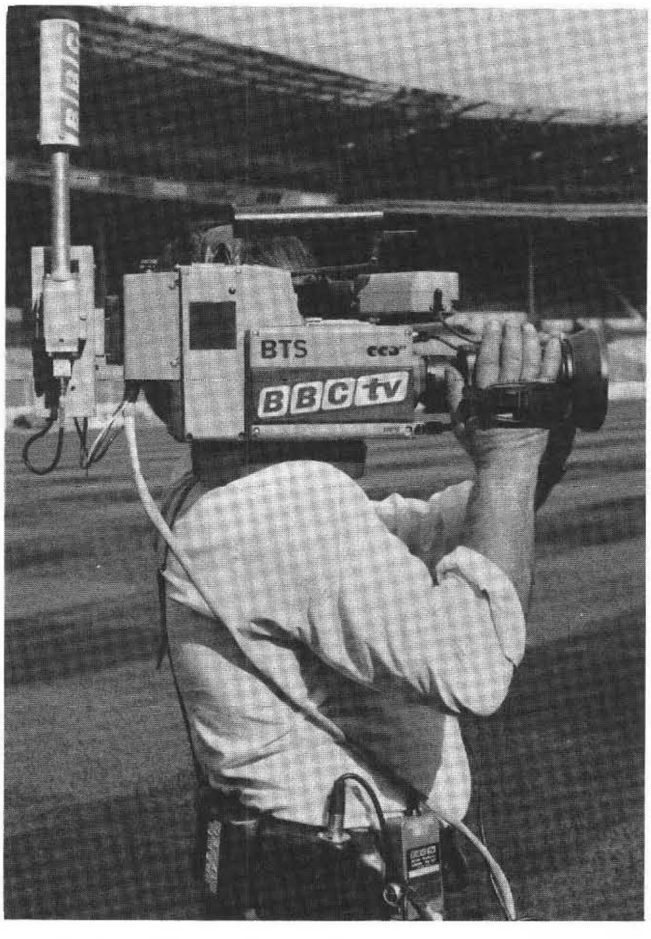


Fig. 10 - The 12 GHz single-operator radio-camera.

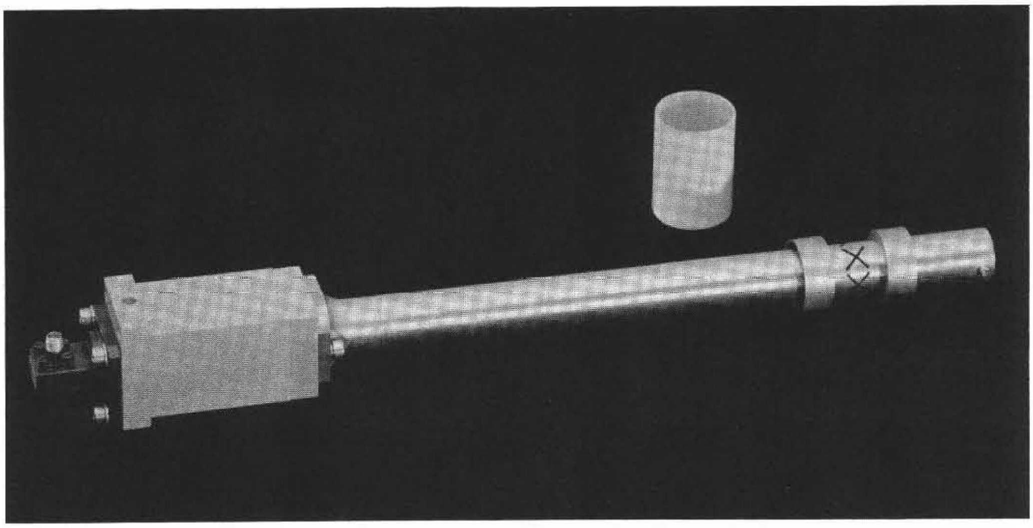
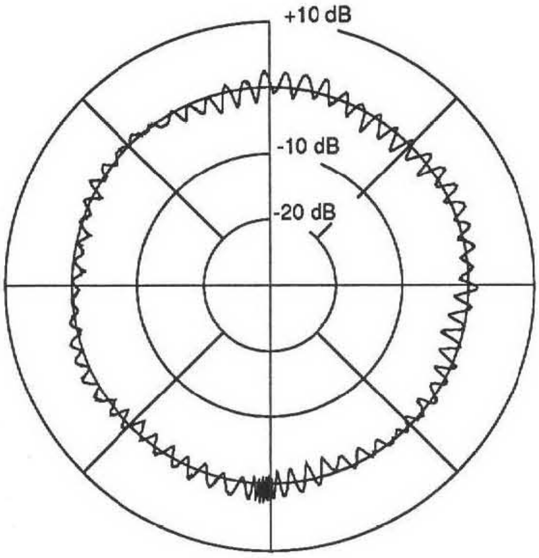
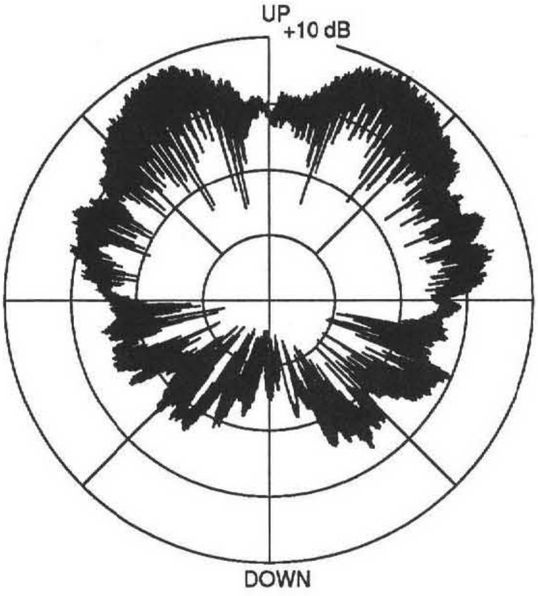


Fig. 11
The 12 GHz transmitting antenna.



(a) Azimuth plane.



(b) Elevation plane.

Fig. 12 - Radiation patterns for the 12 GHz antenna.

Department and is the slotted waveguide which, again, is shrouded by a glass-fibre radome. The polariser can be seen at the bottom of the waveguide tube, and the miniature transmitter (again by RF Technology) is attached to the rear of the camera.

A close-up of the antenna is shown in Fig. 11, where the radome has been removed to show some of the crossed slots. Also apparent are the external choke sleeves, on either side of the slots, which were added to reduce the levels of end-fire radiation.

The axial-ratio radiation patterns for this antenna are shown in Fig. 12, measured in the azimuth and elevation planes.

In the azimuth pattern, shown in Fig. 12(a), the width of the envelope is between 2 dB and 4 dB, and this corresponds to an XPD varying between about 19 dB and 13 dB, respectively. Again, the mean pattern is a circle, showing the required omni-directional response.

The mean of the elevation pattern, shown in Fig. 12(b), is a rather distorted lateral figure ‘8’, but again a good degree of suppression is provided in the downwards direction. The wide beamwidth permits tilting, but in this case the axial ratio has been optimised in the azimuth plane. An axial ratio better than 10 dB (6 dB XPD) is maintained over the important range from 10° below the horizontal to 45° above.

Similar radiation patterns are maintained over the frequency range 11.5 - 13.0 GHz.

5.5 The 12 GHz switched-antenna system

Research work using a small directive transmitting antenna with an electromechanical tracking system, led to the conclusion that a solid-state

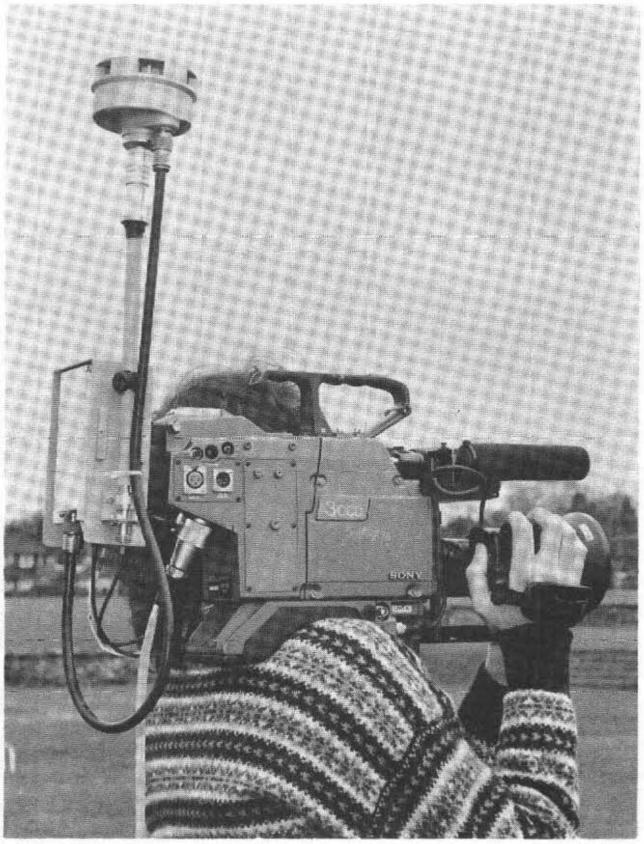


Fig. 13 - An experimental 12 GHz switched-antenna radio-camera.

approach was to be preferred. This led on to the idea of quantising the directions in which the antenna could point, using a number of discrete directive antennas, with electronic switching of the transmitter to one or other of them[6].

This principle is currently being applied to a system using six small horn antennas operating at 12 GHz; this system has the potential to offer even greater resistance to multipath distortion. The horns point in directions spaced by 60° in the azimuth plane and are clustered around a central vertical mounting pole, which can be attached to a portable camera, as illustrated in Fig. 13. The 12 GHz band was chosen to keep the antenna cluster small, but the principle could be applied to other frequencies. Also, other types of directive antenna could be used in a cluster of more or less than six, and these could be pointed in directions away from the azimuth plane.

The initial aim of this system is to keep the transmitting antenna pointing towards the distant receiver, emulating the dual-operator approach. This is accomplished using a control loop which requires a low-bandwidth data link from the receiver back to the radio-camera. The data link can use a VHF or UHF talkback channel and can be made very robust by means of error protection. A simplified block diagram of the system is shown in Fig. 14, and the following explanation will be limited to the case of six transmitting antennas.

During six of the blank lines in each television field-blanking interval, a line-rate test signal is inserted into the outgoing video signal fed to the transmitter. At the same time, the RF signal output by the

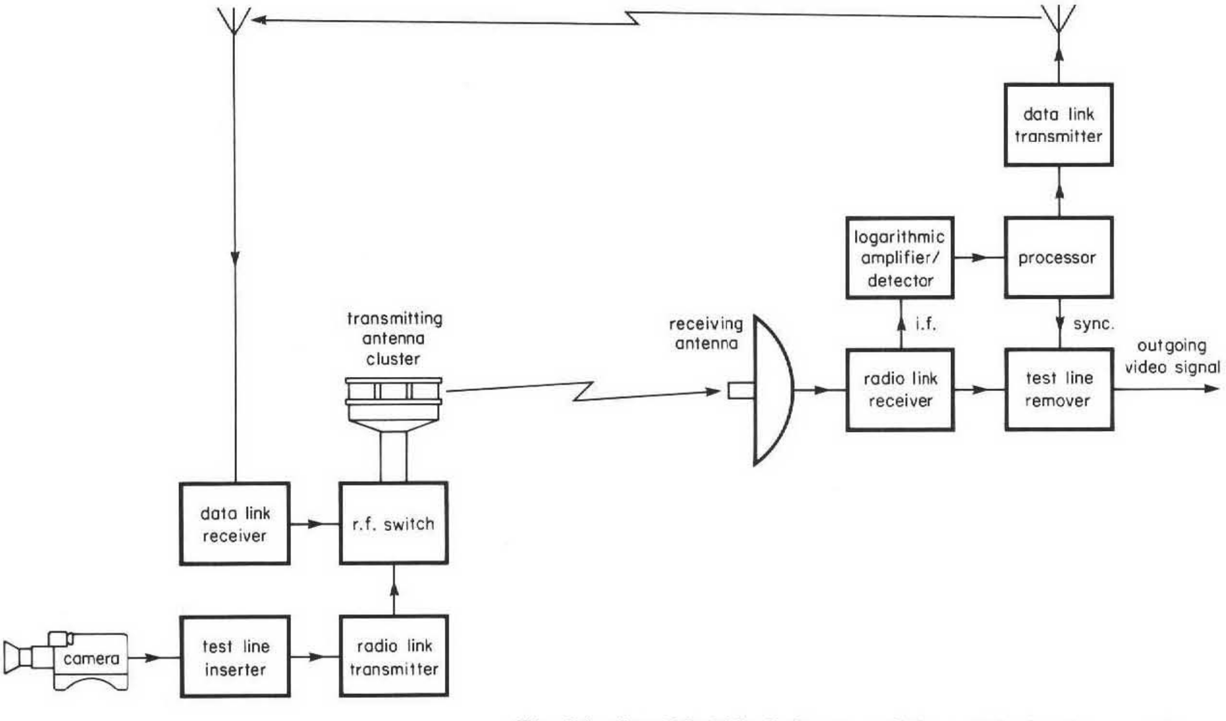


Fig. 14 - Simplified block diagram of the switched-antenna system.

transmitter is directed to each of the six antennas in turn, so for the duration of each test line, the signal is transmitted in a different direction.

At the remote receiver, circuitry synchronised to the incoming television signal is used to assess the quality of the received signal, for each of the six test lines; a sync. separator with a 'heavy flywheel' action is used. A choice is made as to which of the six transmitting antennas offers the highest quality link. Then this is signalled to the radio-camera over the data link, and the chosen antenna is used to transmit the next active television field. Since this approach is adaptive on a field-by-field basis, it can cope with quite rapid movements of the radio-camera and rapidly changing propagation conditions. All the video and RF switching is accomplished during field-blanking intervals, so the received television signal is free from visible artefacts.

A simple way to assess the quality of the received signal is to measure the strength of the RF signal. For this, a logarithmic amplifier/detector is fed with a sample of the intermediate-frequency (IF) signal in the radio-link receiver, taken from a stage which is not subject to AGC. The log. amplifier outputs a voltage proportional to the signal strength measured in decibels. However, this alone takes little account of multipath propagation.

In this case the number of antennas in the cluster is small, so their beamwidths have to be large (about 60°), and this increases the potential for unwanted multipath effects. Also, since the 'tracking' function applies only to the azimuth plane, the antennas need large beamwidths in the elevation plane (at least 50°) to accommodate tilting. The horn cluster is shown in Fig. 15, and the horns are vertical-linearly polarised antennas, although they could be adapted to CP by fitting a circularly polarising screen in front of their apertures. However, this might not be necessary, or even desirable.

The novel feature of this system is that it can 'sound' the propagation path before it uses it, in a six-fold sense, and this is where the inserted test signal is used. A simple way to quantify multipath propagation on a radio link is to transmit a swept-frequency signal, or, since the transmitter uses FM, a 'sawtooth' video waveform. On reception, the 'comb filter' effect modulates the amplitude of the signal as it sweeps, and the amplitude modulation of the IF signal in the receiver can be measured. In practice a special video test waveform is used which contains a swept-frequency subcarrier superimposed on a line-rate sawtooth. It has been found that the shape of this waveform, in the video signal output by the receiver, is consistently distorted when multipath effects are present, so they can be quantified by measuring the distortion of the waveform.

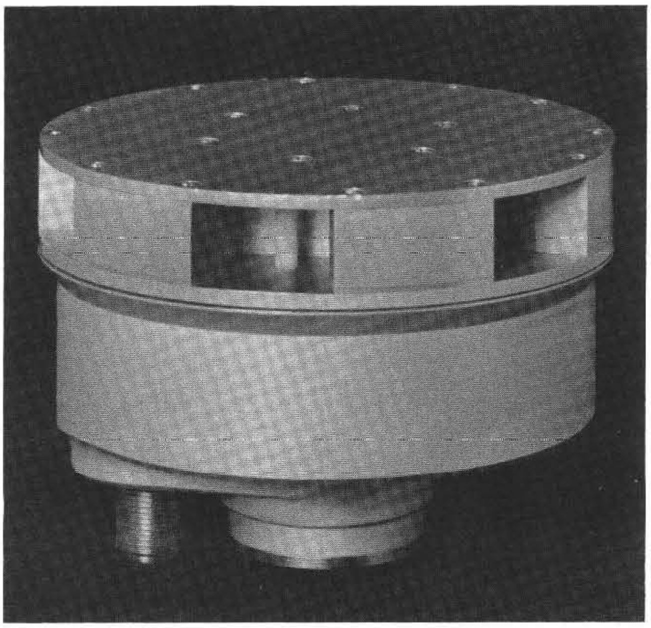


Fig. 15 - The cluster of six horn antennas.

By assessing the degree of multipath distortion, as well as the received signal strength, for each of the six possible propagation paths in turn, a weighted choice can be made. This can, for instance, reject the option of using a transmitting antenna which gives the greatest signal strength if it also gives the worst multipath distortion, and accept an option which gives a smaller, but adequate, signal strength with less distortion.

With this combined assessment, the opportunity is presented for rejecting the antenna which would have transmitted over the direct path and purposely accepting a reflected path which is relatively free from higher-order multipath reflections (i.e. second reflection, etc.). This might even allow communication to be sustained when the direct path is completely blocked, but, of course, this would not be possible if circular polarisation was used.

The circuitry at the transmitting end of the link is miniaturised, and housed in a 'camera pack' occupying a volume no larger than the 12 GHz transmitter shown in Fig. 10. All the processing in the system is handled digitally using transputers, and, at the time of writing, the construction of an experimental set of equipment is nearing completion. The base-station processor is shown in Fig. 16.

With some re-configuration of the building blocks, the same principles can be applied to diversity reception of radio-camera signals, basing the decision to switch between two or more receivers on the degrees of multipath distortion as well as the received signal strengths. This application is also being studied and duplicate experimental hardware is being constructed.

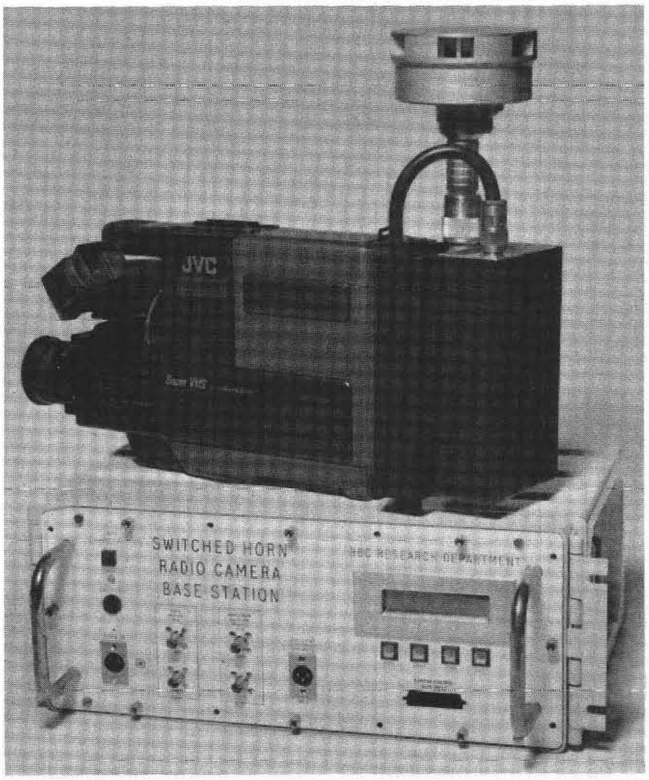


Fig. 16 - The base-station processor with the radio-camera.

6. PRACTICAL USE OF RADIO-CAMERAS

Field trials have shown that the CP systems have a clear advantage over earlier linearly polarised systems. The areas which cannot be covered, owing to excessive multipath distortion, tend to be narrow zones, where small movements of the radio-camera restore the received signal; the linearly polarised systems were affected by large unusable zones. Failure of the radio link appears to occur less abruptly with the 2.5 GHz systems than with the 12 GHz systems, but this is more likely to be a product of the reduced spatial density of the multipath nulls than of the improved 'free-space' link budget.

The 2.5 GHz CP systems have been operational since 1987, and have been used at a large number of sports OBs. The list includes tennis at Wimbledon, the FA Cup Final at Wembley Stadium, the Formula 1 Grand Prix at Silverstone, several horse racing events and many major rugby matches. During 1990 these systems were also used successfully for the coverage of golf; in this case the radio-camera signal was relayed using a 'mid-point' set up in a caddy car.

Since their inception, for the Seoul Olympics in 1988, the 12 GHz CP systems have also been used widely, and notably at the 1990 Commonwealth Games in Auckland.

Both types of system have also been used successfully indoors, for events held at the Royal Albert Hall and Earls Court, as two examples, and on several occasions in television studios.

7. CONCLUSIONS

Dual-operator and vehicular radio-cameras have been in use in the BBC for many years, and their contribution to live television OBs is firmly established; but the successful use of single-operator, hand-portable systems is a relatively new phenomenon, following the development at Research Department of the specialised omnidirectional CP transmitting antennas.

Single-operator radio-camera operation has gained a great deal of acceptance amongst OB producers because of the improved flexibility it offers, even if the radio-link fails occasionally because of excessive multipath propagation. The clear benefit of the CP systems, over the earlier linearly polarised systems, has been demonstrated in field trials. The 2.5 GHz and 12 GHz systems, which have been described, are now used regularly for BBC television productions. These can provide around 80% coverage of the ground area at a typical sports stadium.

In 1990, the Royal Television Society awarded one of the 'Geoffrey Parr' awards for technological achievement to the BBC, recognising the contribution to television technology made by the development and use of single-operator radio-camera systems in the BBC.

The construction of experimental equipment to test the switched-antenna radio-camera principle is nearing completion, and soon we will be conducting field trials. In a very basic experimental form, this equipment already out-performs the earlier electromechanical system, and the expectation is that this system will allow even greater coverage than the omnidirectional CP systems in a heavily cluttered environment. The system can also be re-configured for diversity reception, and in the future, this might facilitate the extensive use of radio-cameras in television studios.

Perhaps the only remaining advantage of the dual-operator system, with its greater operating cost, is that the second operator can remain aware of the environment whilst the camera operator concentrates on the viewfinder. This has been found to be particularly important when operating at motor racing circuits!

8. ACKNOWLEDGEMENTS

The assistance of Dr. Ing. R. Salvadorini, and his colleagues at the RAI Research Centre in Turin, is acknowledged for demonstrating to us the RAI radio-camera system using a Lindenblad array for the transmitting antenna.

Contributions to the work reported here are acknowledged from Bruce Devlin, formerly of Research Department, who did much of the development work on the CP antennas, and from John Scott and his colleagues at BBC Television Outside Broadcasts, who have provided a great deal of assistance with field trials and now make extensive use of the radio-camera systems described here.

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APPENDIX 1

Link Budgets for Typical Radio-camera Systems

The performance of a radio link can be judged by the signal-to-noise (S/N) ratio achieved at the end of the link, with the target S/N ratio for most OB links being 46 dB unweighted, or about 57 dB with Unified weighting. This does not mean that a link offering a smaller value of S/N would not be used in practice; its performance may be judged in view of the benefit it offers. Thus a radio-camera link providing only 50 dB Unified weighted might still be considered usable.

The significant parameters of a radio link can be expressed in decibel form in a link budget, giving the ultimate S/N ratio as the result, and then the influence of variables such as the length of the propagation path can be assessed. The following two examples represent typical radio-camera links.

The first example is for a 2.5 GHz system using an omnidirectional transmitting antenna (similar to a dipole) and a 1.1 m reflector antenna at the receiver. For the sake of simplicity, only free-space propagation conditions are considered and the path length is taken as 1 km:

	Transmitter power	200 mW	−7.0 dBW
+	Transmitting antenna gain		2.0 dBi
−	Free-space propagation loss		100.4 dB
+	Receiving antenna gain		25.0 dBi
=	Received carrier power		−80.4 dBW
	Receiving antenna noise temperature	290 K	
+	Receiver noise temperature (7 dB NF)	1160 K	
=	Total noise temperature	1450 K	31.6 dBK
+	Effective noise bandwidth	30 MHz	74.8 dBHz [1]
+	Boltzmann constant		−228.6 dBW/Hz/K
=	Received noise power (in 30 MHz bandwidth)		−122.2 dBW
	Received C/N ratio (in 30 MHz bandwidth)		41.8 dB
+	Relationship between S/N and C/N		15.6 dB [2]
=	Received unweighted S/N ratio		57.4 dB
+	Unified weighting		11.2 dB [3]
=	Received Unified-weighted S/N ratio		68.6 dB

Notes:

[1] Although the receiver bandwidth, determined by an IF filter, is usually about 30 MHz, the RF channel bandwidth is often limited to slightly less than 20 MHz by an external filter in a 'multiplexer'. This is necessary because the frequency plan for the 2.5 GHz band has channels spaced by 20 MHz. A different RF bandwidth does not affect the resulting S/N ratio as long as it is greater than the minimum, 'Carson' bandwidth (i.e. twice the baseband-width plus the FM peak-to-peak deviation) and the C/N ratio exceeds the 11 dB threshold.

[2] For 8 MHz FM deviation using CCIR Rec. 405 pre-emphasis for 625-line PAL.

[3] This value is taken from CCIR Rep. 637-1.

The relationship between the path length and the S/N ratio (expressed as a fraction rather than in dB) is an inverse square law so, for instance, halving the path length will give a S/N ratio 6 dB greater. The value obtained in this example is well in excess of the target value, and in practice the path length will usually be less than 1 km, so a significant margin exists in this case. However, in practice other factors such as multipath propagation and mis-pointing of the receiving antenna may reduce the actual value of S/N ratio obtained.

The second example is for a 12 GHz system using an omnidirectional transmitting antenna and a 0.6 m reflector antenna at the receiver. Again, only free-space propagation conditions are considered and the path length is taken as 1 km:

	Transmitter power	20 mW	−17.0 dBW
+	Transmitting antenna gain		0.0 dBi
−	Free-space propagation loss		114.0 dB
+	Receiving antenna gain		34.0 dBi
=	Received carrier power		−97.0 dBW
	Receiving antenna noise temperature	290 K	
+	Receiver noise temperature (10 dB NF)	2610 K	
=	Total noise temperature	2900 K	34.6 dBK
+	Effective noise bandwidth	30 MHz	74.8 dBHz
+	Boltzmann constant		−228.6 dBW/Hz/K
=	Received noise power (in 30 MHz bandwidth)		−119.2 dBW
	Received C/N *ratio (in 30 MHz bandwidth)*		22.2 dB
+	Relationship between S/N and C/N		15.6 dB
=	Received unweighted S/N ratio		37.8 dB
+	Unified weighting		11.2 dB
=	Received Unified-weighted S/N ratio		49.0 dB

With this value of S/N ratio the link would probably be considered usable for a conventional OB, but in view of the other factors which may reduce its value, the margin in this case would certainly be considered small.

APPENDIX 2

The Effects of Multipath Propagation

Introduction

When an FM television signal is transmitted over a path which is subject to multipath propagation, the video modulation of the received signal can be affected adversely in a number of ways. Using simplified theory, it is possible to gain some insight into the mechanisms by which these effects are caused. Firstly, considering the transmitted signal as a simple, continuous wave, it will be shown that multipath propagation causes the RF channel to exhibit an uneven frequency response. Then, by considering the application of sinusoidal FM with a constant modulation index, it will be demonstrated that the modulation index of the received signal can be modified by this frequency response. When this principle is applied to the case where the modulating waveform is a PAL video signal, an explanation is provided for the chrominance differential gain effects which are probably the most obvious manifestation of multipath propagation in radio-camera links.

Several approximations will be used in the following calculations, so they are not intended to be rigorous proofs. Initially, the simplified scenario of Fig. A2.1 will be considered, shown as a plan view, using omnidirectional transmitting and receiving antennas, a clear direct propagation path and a single reflected path. The receiver and reflecting object (or 'reflector') will be considered as stationary, and later the effect of moving only the transmitting radio-camera will be considered. For simplicity the reflector will also be considered as 'omnidirectional', that is, giving rise to reflected (or diffracted) signals in all directions, as would be the case if the object was a vertical pole with a large diameter in terms of the wavelength. In practice, a directive receiving antenna would most likely be used, a real reflector could be less uniform, and a large number of reflectors could be present giving rise to many additional reflected paths.

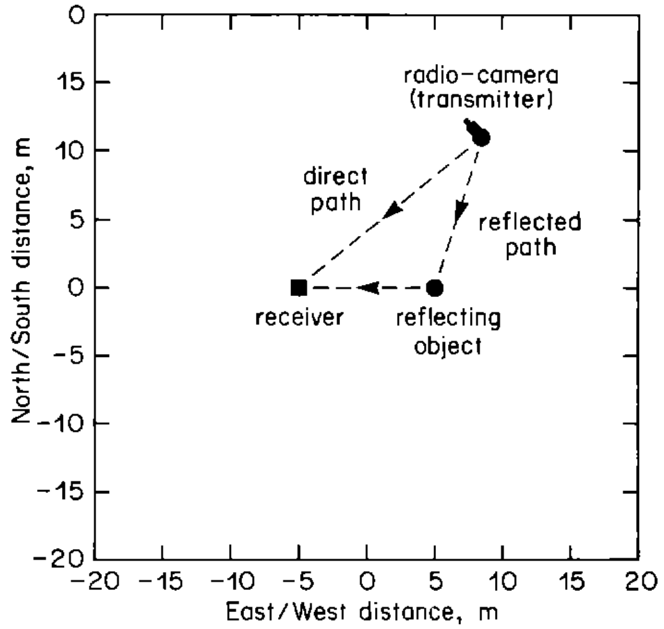

Fig. A2.1 - A radio-camera link with multipath propagation: plan view of a 40 × 40 m square.

Frequency response of the RF channel

Initially, the transmitted signal will be taken as a continuous wave of unit amplitude:

$$e_T(t) = \cos \omega t.$$

If the attenuation imposed by the direct propagation path is α, and its time delay τ, then the signal received over the direct path is:

$$e_D(t) = \alpha \cos \omega(t - \tau).$$

Since the direct signal propagates over a clear, line-of-sight path the reflected signal will always be subjected to a larger attenuation and a greater time delay because it has to travel further. We are dealing with field strengths (i.e. amplitudes) here, so the additional attenuation due to spreading of the transmitted wave, R, is equal to the ratio of the lengths of the direct and reflected paths ($R \leq 1$). The time delay for propagation over the reflected path can be written as $\tau + \delta$, where the additional delay, $\delta = D/C$, where D is the difference between the lengths of the two paths and C is the velocity of electromagnetic propagation in air.

The action of reflecting a signal by 'scattering', or re-transmission, tends to be lossy for most practical reflectors other than continuous conductive surfaces. Therefore the total attenuation for the reflected path can be written as $\alpha\, R\, \rho$, where ρ is the magnitude of the effective voltage-reflection coefficient of the reflector. Also, a phase shift, ϕ (radians), will be imposed on this signal at the reflecting boundary on account of the phase of the voltage-reflection coefficient.

In general, the values of ρ and ϕ are related to the radio frequency, the polarisation tilt angle and angle of incidence of the radio wave, the conductivity and permittivity of the reflecting surface, its physical size and its surface roughness or curvature. The size and roughness, both expressed in terms of wavelengths, are sometimes combined into an effective 'scattering cross-section'; in radar terminology this is known as the 'radar cross-section'. When reflection occurs at a large, continuous, plane boundary, such as the ground, both ρ and ϕ can be found using the Fresnel expressions[7], but in more complicated cases these only provide approximate values.

The limiting case of a large, plane, metallic reflector is particularly important because it yields the same values of $\rho = 1$ and $\phi = \pi$ radians (or 180°) for a linearly polarised wave with any tilt angle (e.g. horizontal or vertical). A circularly polarised wave can be resolved into two linearly polarised components with tilt angles separated by 90° and a quadrature phase relationship. The sense of rotation (right-hand or left-hand) is dictated by the sense of the phase relationship (i.e. which component leads the other) and the direction of propagation. When this wave is reflected the phases of both components are shifted by 180°, so the phase relationship is not changed, but in the case of normal incidence the direction of propagation is simply reversed so the sense of circular polarisation is reversed. Because the relative permittivity is zero and the conductivity is very large for a metallic reflector ($>10^7$ S/m for copper), the Fresnel expressions show no sensitivity to the angle of incidence so the effect is essentially the same for all variations of the geometry.

Antennas can be made to discriminate in favour of one particular sense of circular polarisation, so this effect provides a degree of suppression of unwanted signals arising from single (and other odd-order) reflections caused by metallic surfaces. This suppression can be considered as a further reduction of the value of ρ. If the XPD of the transmitting antenna is about 10 dB, and that of the receiving antenna is considerably greater, as would be expected for the usual, directive receiving antenna, ρ could be reduced to about 0.3 of its initial magnitude. This effect does not occur with a linearly polarised wave because there is only one component, and its tilt angle is independent of the direction of propagation.

In less idealised cases, with smaller, rough, non-planar or non-metallic reflectors, and when the geometry of the reflection is not normal incidence, the degree of suppression, and hence the benefit of circular over linear polarisation, is diminished. However, in practice, radio-cameras using circularly polarised antennas have been found generally to be much more resistant to multipath effects.

Returning to the general case, the signal received over the reflected path is:

$$e_R(t) = \alpha\, R\, \rho \cos\left[\omega(t - \tau - \delta) + \phi\right]$$

and on reception, the direct and reflected signals will be combined. The receiver will then respond to the algebraic sum of the two phasors $e_D(t)$ and $e_R(t)$, as illustrated in Fig. A2.2. The magnitude of the resultant is given by:

$$A = \alpha\left[1 + R^2 \rho^2 + 2R\, \rho \cos(\omega\, \delta - \phi)\right]^{1/2}.$$

Normalising to the mean attenuation, α, and taking $\phi = \pi$, this function has the form illustrated in Fig. A2.3 when plotted with respect to the frequency of the signal, $\omega / 2\pi$ Hz. For this example $\delta = 6.7$ ns, corresponding to a 2 m difference in path lengths. The maxima have magnitudes of $(1 + R\, \rho)$, which can reach a peak value of 2 (or +6 dB), and the minima have magnitudes of $(1 - R\, \rho)$, which can drop to zero (or minus infinity dB). Clearly, the transmission minima can have greater effect on the received signal than the maxima.

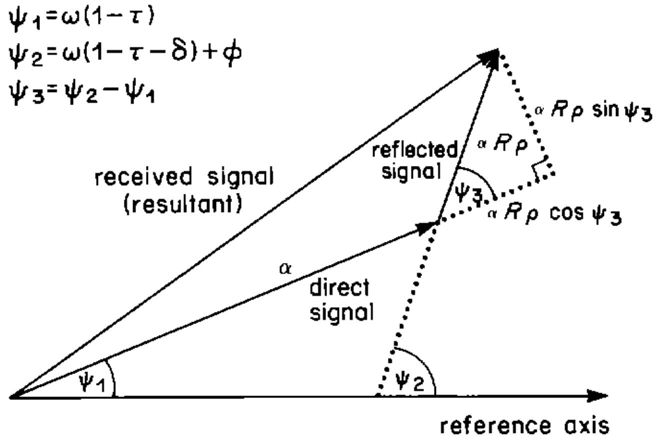

Fig. A2.2 - Formation of the received signal by phasor summation.

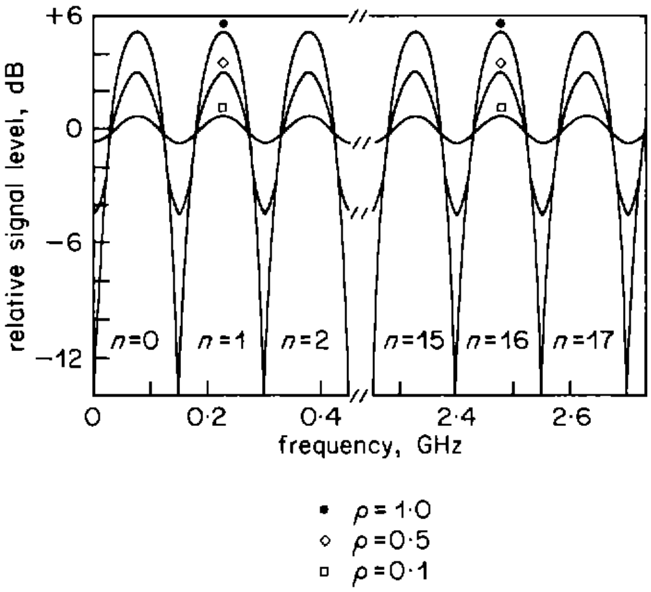

Fig. A2.3 - Magnitude of the received signal vs. frequency.

Variation with movement of the transmitter

The way in which R changes with the location of the radio-camera is illustrated in Fig. A2.4, which shows contours of constant R, expressed in dB*, for $\rho = 1$, and 10 m spacing between the reflector and the receiver. Contours for these values would have the same shapes for any other spacing; their size would simply be scaled. Thus, the transmission minima will have greatest depths when the radio-camera is located near to the reflector, or when the angle of reflection is large; the geometrical arrangement known as 'grazing incidence'.

The minima occur at frequencies for which:

$$\omega\,\delta - \phi = m\,\pi$$

where $m = 1, 3, 5$, etc., or alternatively:

$$\omega\,\delta - \phi = (1 + 2n)\,\pi$$

where $n = 0, 1, 2$, etc. Converting from radians to degrees, the boundary phase shift can be expressed as $\theta = (\phi \,.\, 180/\pi)$ degrees. Also, the frequency can be written as $f = (\omega \;/\; 2\,\pi)$ Hz, and the delay difference can

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* The contours in this figure are numbered with values corresponding to $20\log_{10}R$, which is the decibel difference between the spreading attentuations for the direct and reflected paths.

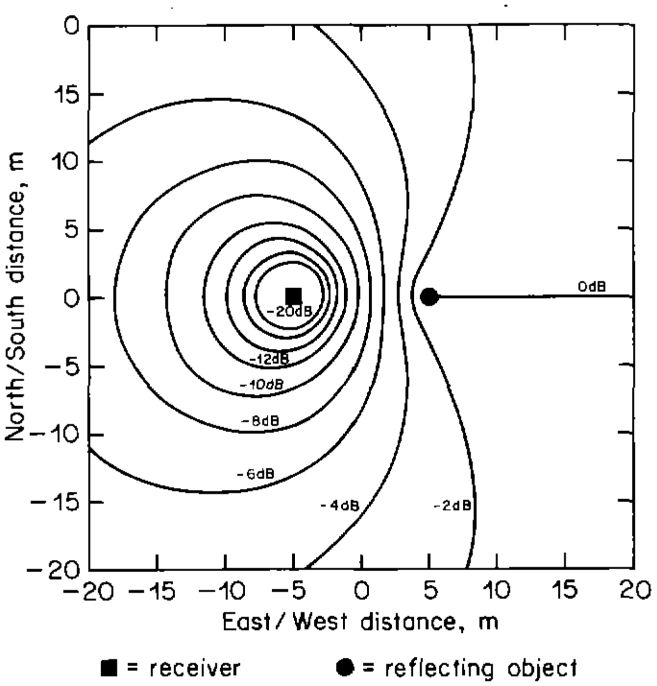


Fig. A2.4 - Contours of constant path-length ratio, expressed in dB: plan view of a 40 × 40 m square.

be given in terms of the path-length difference as $D = C\,\delta$. Then:

$$f = C(1 + 2n + \theta / 180) / 2D$$

and the frequency spacing between the minima is the differential of this function (setting $\Delta n = 1$):

$$\Delta f = C / D$$

that is, the frequency for which D is effectively the wavelength.

The value of D depends on the relative positions of the radio-camera, the reflector and the receiver, so as the radio-camera moves around, the frequencies of the transmission minima will change. If D is made the subject of the equation and f is replaced by the wavelength, $\lambda = C / f$, then:

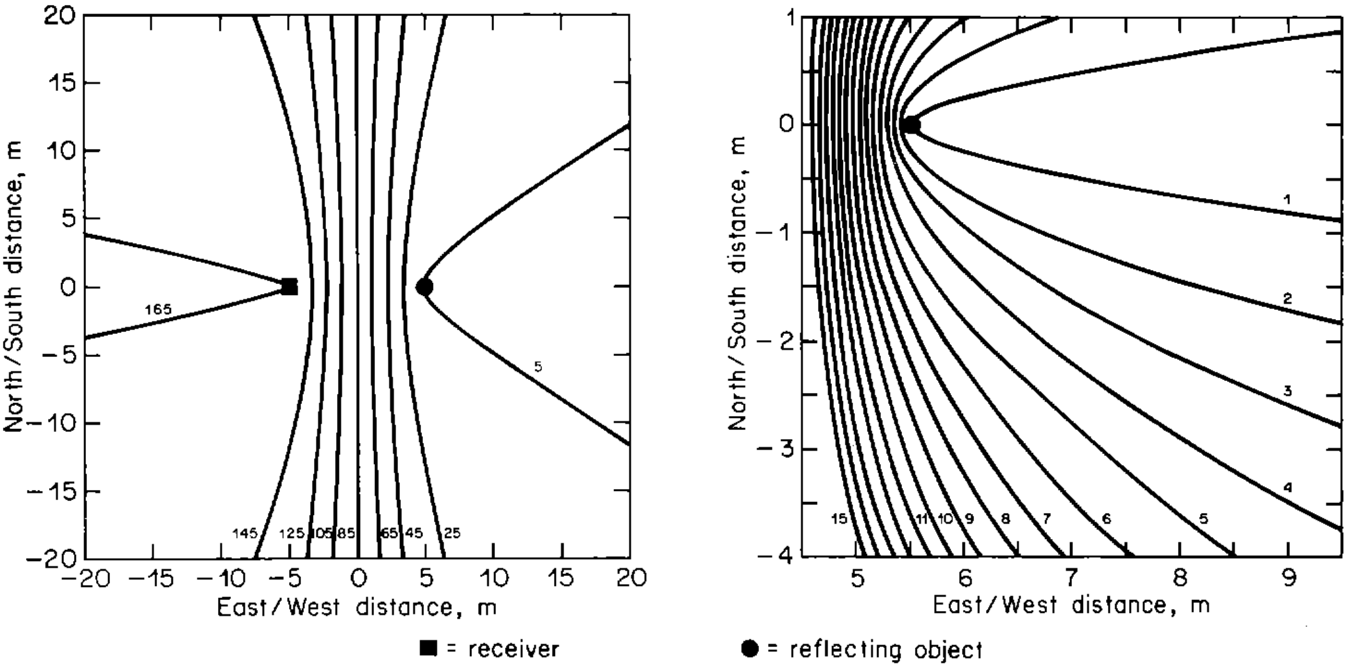
$$D = (1 + 2n + \theta / 180)\,\lambda / 2$$

and by differentiating again (setting $\Delta n = 1$):

$$\Delta D = \lambda$$

so, for a given frequency, the incremental change of D needed to pass from one minimum to another is one wavelength. Therefore, the two-dimensional spatial distribution of locations where a transmission minimum will occur at a fixed frequency is a family of curves which are contours of constant D, between which D varies by one wavelength, or n varies by one.

Examples of such contours are illustrated in Fig. A2.5(a) for the fixed frequency of exactly 2.5 GHz. Again, this is a plan view with 10 m spacing between the reflector and receiver, and the corresponding value of n is shown for each contour (the number of whole wavelengths of D). For clarity, only a small sample of all the possible contours has been drawn; every twentieth for $n \geq 5$. A clearer picture of what happens near the reflector can be gained from Fig. A2.5(b), which covers the range of n from 1 to 15. Again, the shapes of the contours are not dependent on the spacing, but, obviously, the number of integer values of n for which contours can be drawn depends on the spacing. In this simplified scenario the curves are hyperbolae having the receiver and reflector at their foci, but in less idealised cases the curve shapes will be somewhat more complicated. Nevertheless, the greatest density of contours will still occur in the region(s) between the reflector(s) and the receiver.



(a) Plan view of a 40 × 40 m square.

(b) Close-up of the region near the reflector.

Fig. A2.5 - Contours of constant path-length difference, expressed in wavelengths for a frequency of 2.5 GHz.

From the preceding discussion it can be observed that:

(a) The frequencies of the minima depend on the relative locations of the transmitter, receiver and reflector, so the frequencies will change when any of these three items moves with respect to another. Consequently, the appearance of a minimum at a particular spot frequency tends to be a transient event when the transmitter is mobile.

(b) The depths of the minima increase as the ratio of the path lengths, R tends towards its maximum value of unity (or 0 dB as in Fig. A2.4). The depths are also affected by the reflection coefficient of the reflector, ρ, and when both have values close to unity (e.g. grazing incidence on a metallic reflector) a very low signal strength will be received if the signal frequency coincides with a transmission minimum. However, in this case the geometry dictates that D must be small, so the minima will be relatively widely spaced in frequency. If this spacing is considerably greater than the bandwidth of the transmitted signal the result is what is known as 'flat' fading. This case applies for radio-camera locations near to, and to the right of, the reflector in Figs. A2.4 and A2.5.

(c) When D is large, R will be small (or minus many dB), so the transmission minima will be shallow, but the spectral density of minima will be relatively great. If the frequency spacing of the minima is less than the bandwidth of the transmitted signal the result is 'selective' fading. This case applies for locations near to, and to the left of, the receiver in Figs. A2.4 and A2.5.

(d) In Fig. A2.5 the greatest spatial density of contours occurs in the region between the reflector and the receiver, and here the most rapid fluctuations of received signal strength would be expected as the radio-camera moved.

(e) For a given geometry, at any location, both the spectral density and the spatial density of the transmission minima will increase with increasing signal frequency, or shorter wavelength.

Effects on modulated signals

Frequency modulation will now be applied to the transmitted signal to examine the effects of the uneven frequency response of the RF channel. To simplify calculations, a simple sinusoidal modulating waveform will be considered, as is the case when the modulating signal is a video waveform containing just colour subcarrier, for example during the colour burst. Also, the FM signal will be considered as narrow-band, having a modulation index, or peak phase deviation, β, much smaller than 1 radian.

In practice β can approach 1 radian when the picture contains large-amplitude high-frequency luminance components or highly saturated colours because pre-emphasis is normally used on OB radio links. For the example of the colour burst, with a nominal modulation sensitivity of 8 MHz/V, which is the common value for such links, the actual value of β is 0.36 radian.

Note that the modulation sensitivity of an FM transmitter is usually quoted for the 0 dB frequency of the pre-emphasis characteristic, and for the common CCIR Rec. 405 pre-emphasis used with 625-line television this is 1.512 MHz. Also, with this characteristic, low-frequency components of the video signal are attenuated by 11 dB so for a nominal sensitivity of 8 MHz/V the 'static' (i.e. LF) deviation sensitivity is 2.25 MHz/V.

Using the conventional notation for a narrow-band FM (NBFM) signal, the unit amplitude transmitted signal can be written as:

$$e_T = \cos(\omega_c t + \beta \sin \omega_m t)$$

where ω_c is the angular frequency of the carrier (the rest-frequency of the signal in the absence of modulation), and ω_m is the angular frequency of the modulating waveform. Expanding this with $\beta \ll 1$:

$$e_T \approx \cos \omega_c t - \beta \sin \omega_c t \,.\, \sin \omega_m t$$

then

$$e_T \approx \cos \omega_c t - \tfrac{1}{2} \beta \cos(\omega_c - \omega_m)t + \tfrac{1}{2} \beta \cos(\omega_c + \omega_m)t.$$

This approximation gives the familiar group of three spectral components for an NBFM signal; the carrier, the lower sidetone and the upper sidetone. This is illustrated as a vector diagram in Fig. A2.6(a).

Now if we consider this signal passing through the RF channel affected by multipath propagation, we could, for instance, picture a transmission minimum falling on the carrier frequency. If Δf, the frequency spacing of the minima, was much greater than the bandwidth of the FM signal, in this case ω_m/π Hz, the carrier and sidetones would be attenuated by similar amounts and the result would be a simple reduction in the received signal strength; the principle known as 'flat' fading. If the minimum was very deep this could cause the demodulator in the receiver to operate below its FM threshold, and it would then output a very noisy signal.

Alternatively, with a smaller value of Δf, 'selective' fading could occur. For example, if the carrier term was attenuated much more than the sidetones, this would have the same effect on the above approximation as increasing β, so the modulation index of the received signal would be magnified. Conversely, minima occurring symmetrically above and below the carrier frequency would tend to diminish the modulation index.

Another possible case of 'selective' fading is where one of the sidetones is attenuated with respect to the other two terms. Taking, for example, the upper sidetone and applying an attenuation μ, where $\mu < 1$, the approximation becomes:

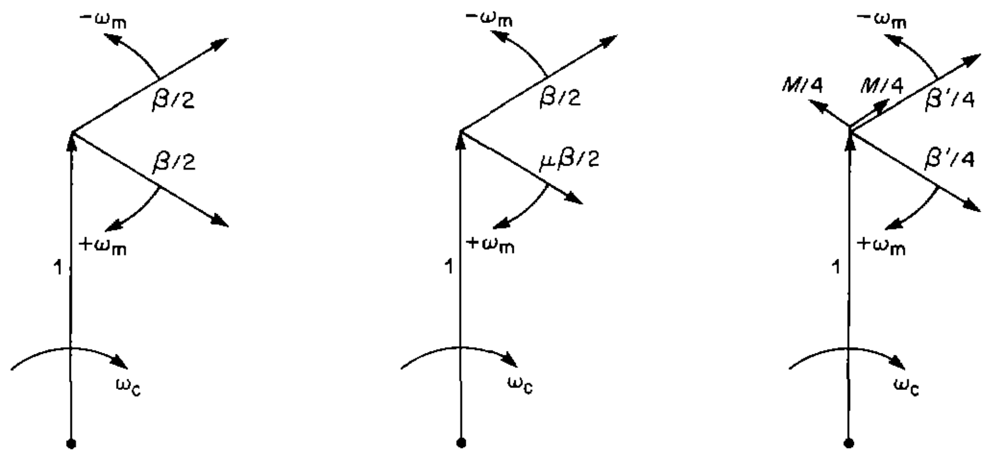
$$e_T \approx \cos \omega_c t - \tfrac{1}{2} \beta \cos(\omega_c - \omega_m)t + \tfrac{1}{2} \mu \beta \cos(\omega_c + \omega_m)t.$$

This is illustrated with vectors in Fig. A2.6(b), and can be re-written as:

$$e_T \approx \tfrac{1}{2}[\cos \omega_c t - \tfrac{1}{2} \beta' \cos(\omega_c - \omega_m)t + \tfrac{1}{2} \beta' \cos(\omega_c + \omega_m)t]$$

$$+ \tfrac{1}{2}[\cos \omega_c t + \tfrac{1}{2} M \cos(\omega_c - \omega_m)t + \tfrac{1}{2} M \cos(\omega_c + \omega_m)t].$$

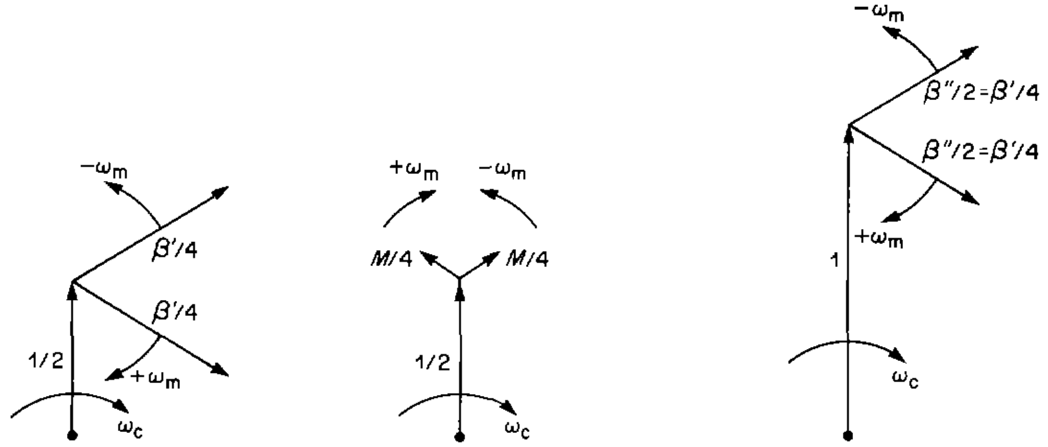
The first group of terms in square brackets corresponds to an FM signal of half the original amplitude with a different modulation index, $\beta' = \beta\,(1 + \mu)$. The second group corresponds to an AM signal with a carrier amplitude half that of the original signal, an AM modulation index, or peak amplitude variation, of $M = \beta\,(1 - \mu)$, and the same carrier and modulation frequencies. This decomposition of the affected signal into FM and AM components is illustrated in Figs. A2.6(c), (d), and (e); the half-and-half division of the carrier amplitude between the FM and AM components is arbitrary and will have no effect on the result of this discussion.



(a)
The transmitted FM signal.

(b)
The received signal affected by multipath propagation.

(c)
Decomposition into FM and AM components.



(d)
The FM component.

(e)
The AM component.

(f)
The resulting signal after amplitude limiting.

Fig. A2.6 - Vector diagrams showing how multipath propagation can alter the effective modulation index of an FM signal.

When this composite signal is applied to a practical FM radio-link receiver, operating within its normal dynamic range, the amplitude modulation will be removed by the limiter ahead of the FM demodulator. The non-linear amplitude characteristic of the limiter will level the AM signal to its mean, carrier level, so the two terms containing M will disappear leaving the carrier term, ½ cos $\omega_c t$. The signal output by the limiter, which will then be passed to the demodulator, can then be written as:

$$e_{LIM} \approx \cos \omega_c t - \tfrac{1}{2} \beta'' \cos(\omega_c - \omega_m)t + \tfrac{1}{2} \beta'' \cos(\omega_c + \omega_m)t$$

where $\beta'' = \beta' / 2 = \beta (1 + \mu) / 2$, and is smaller than the original modulation index. This is illustrated in Fig. A2.6(f). Therefore the modulation index of the received signal will be diminished if a transmission minimum falls on either of the sidetones independently.

Of course, this is a greatly simplified explanation, and a practical limiter may introduce a number of other non-linear effects, such as AM to PM conversion which could lead to further modification of the effective modulation index. Also, consideration has only been given to the magnitude of the received signal, and inspection of the phase would reveal that harmonic distortion components can be generated in the received modulating waveform. Furthermore, the NBFM aproximation (that $\beta \ll 1$) is not strictly valid for the general case, and for accuracy, higher-order sidetones may need to be considered; with a typical RF bandwidth of 20 MHz the second-order sidetones due to colour subcarrier may be significant.

Since multipath propagation can also be interpreted as co-channel interference, where the interfering signal has the same modulation as the wanted signal but with different timing, some other adverse effects can occur if δ becomes a significant fraction of the television line period ($\geq 0.5\ \mu s$). These include the generation of discrete 'echoes' in the received television signal. Such effects have been found to become perceptible on FM radio links at an effective carrier-to-interference ratio (C/I) of about 20 dB. At 2.5 GHz this could occur if D became greater than 150 m, or 1250 wavelengths, and if the product of R and ρ became greater than 0.1 (−20 dB).

If the scenario of Figs. A2.4 and A2.5 was magnified to have, for instance, 100 m spacing between the reflector and receiver, this would clearly be possible at radio-camera locations near to the receiver. However, in practice the directivity of the receiving antenna provides additional suppression of the reflected signal in most cases. This does not help when the radio-camera, the reflector and the receiver are all in line, but in that case the 'normal incidence' reflection is usually suppressed adequately by circular polarisation. Consequently, discrete echoes are seldom seen in television pictures provided by modern radio-camera systems.

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